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DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
WASHINGTON, D.C.

25 May 1953

Report No. 707

(Special)

Copy No. 15

STEAM-JET CONDENSER FOR HYDRODUCTOR PROPULSION SYSTEM



Contract N6ori-10
Task Order I
Project NR 220 003

SECURITY INFORMATION

25 May 1953

Report No. 707
(Special)

RESEARCH AND DEVELOPMENT ON THE STEAM-JET CONDENSER
FOR THE HYDRODUCTOR PROPULSION SYSTEM

Contract N6ori-10
Task Order I
Project NR 220 003

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CONTRACT FULFILLMENT STATEMENT

This special report is submitted in partial fulfillment of Contract
N6ori-10, Task Order I.

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SUMMARY

The small-scale steam-jet condenser test program has been completed with very satisfactory results. The development phase of the program has resulted in the design of a unit which appears to satisfy the requirements of the original problem: a system which will operate with reasonable performance at all depths to 1000 ft. The data obtained have been correlated and are presented herein as a series of curves from which design points may be selected from the performance requirements at the desired operating conditions. In addition to these immediate results, valuable experience has been gained in a relatively new field of underwater propulsion.

Successful test-firings have been performed on a full-scale steam-jet condenser utilizing a 4.5-in.-dia Alc0 motor. These tests have demonstrated the validity of the small-scale investigation and have proved the feasibility of the hydroductor principle.

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I. INTRODUCTION

A. An underwater missile such as the Alclo hydroduct is propelled by a jet of high-velocity steam exhausting through a DeLaval nozzle. However, as the missile achieves greater depth and the back pressure increases, the steam velocity decreases until the thrust of the system deteriorates and the power plant becomes unoperative. This phenomenon imposes a limitation on the missile and restricts its maximum service depth to a value governed by the pressure in the combustion chamber. By condensing the exhaust with a steam-jet condenser, a low back pressure on the steam nozzle can be maintained, and the performance of the missile can be increased and made relatively insensitive to depth. Since the exhaust of the Alclo hydroduct consists of steam and solid reaction products, and is therefore completely condensable, a direct-contact condenser can be applied to the system. When the steam-jet condenser is applied to the hydroduct, the device is termed a hydroductor.

B. With these objectives in mind, a research and development program was undertaken under the auspices of the Office of Naval Research, and actual testing was begun in February of 1952. This report has been prepared to correlate all the information obtained from the development program and presents the results in the form of design parameters and curves from which an engineering design of a prototype unit may be readily accomplished.

II. GENERAL DISCUSSION

A. The hydroductor propulsion system is shown in Figure 1. The energy source of the power plant is a solid-propellant grain consisting of compressed aluminum and potassium perchlorate particles. Upon ignition, these two substances react with each other in a thermitic process to release large quantities of heat. Water, under ram pressure, is sprayed into the heat chamber in such quantity as to produce wet steam, the pressure of which is maintained at an optimum value by a properly designed, supersonic exhaust nozzle.

B. The supersonic exhaust nozzle directs the steam into a condensing and mixing chamber. Sufficient quantities of sea water to condense the steam are ducted into the chamber through external scoops. The design of the sea-water inlet orifices in the scoop is such that the total pressure head, equal to the sum of ram and static pressure heads, is totally converted to velocity head. The pressure within the mixing chamber is the vapor pressure of the condensed mixture, which amounts to only a few pounds per square inch absolute. This condition results in an extremely high steam-exhaust velocity by permitting expansion from the initial conditions down to a very low enthalpy level.

C. Through impact and an exchange of momentum between the steam and water particles, the resultant mixture achieves high velocity at the end of the condensing chamber. After leaving the condensing chamber, the high-velocity mixture passes through a diffuser, where a portion of the velocity

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II General Discussion, C (cont.)

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is converted into pressure head, matching the ambient conditions of the particular depth where operation is taking place. The reaction products at operating temperatures will be solids, and the stream will be totally condensed within the mixing chamber, thereby giving a vehicle with no gaseous wake.

D. Among the problems introduced by a system of this type are: the extremely high rate of condensation of steam for the size of condensing chamber; the efficient diffusion of a high-velocity, highly turbulent mixture of water and steam; and the ability of the system to start readily and maintain stable operation during rapid changes in conditions which accompany the descent of the missile to great depths. The results reported herein will illustrate the extent to which the development program has overcome these and various other problems.

III. THEORETICAL ANALYSIS*

A schematic diagram of the steam-jet condenser as related to the following analysis is included as Figure 2.

A. STEAM NOZZLE

Assuming substantially isentropic expansion through the steam nozzle and accounting for losses by applying a nozzle velocity coefficient, the velocity of the steam jet, V_s , may be expressed as

$$V_s = 223.7 C_s \sqrt{H_s - H_c} \quad (1)$$

B. WATER INJECTOR

1. The expression for the inspouting water velocity, V_w , based on conversion of the total external pressure head to vacuum in the condensing chamber, is

$$V_w = 8.04 C_w \sqrt{\frac{V^2}{2g} + P_d - P_c} \quad (2)$$

2. The water mass rate of flow, M_w , assuming that the length of passage is sufficient to ensure full flow and no contraction of the jet, is given by

$$M_w = A_w V_w W \quad (3)$$

* A list of the symbols employed in this analysis appears on page 12 of this report.

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III Theoretical Analysis (cont.)

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C. CONDENSING CHAMBER

1. The resultant mixture velocity, V_t , based on the assumption of a constant-pressure mixing process and conservation of momentum in the mixing chamber, is calculated from the equation

$$M_s V_s + M_w V_w \cos \theta = (M_s + M_w) V_t \quad (4)$$

The angle θ is usually in the range of 10° to 15° , and therefore $\cos \theta$ is greater than 0.97, making the effect of the small angle negligible. The mixture velocity is thus

$$V_t = \frac{M_s V_s + M_w V_w}{(M_s + M_w)} \quad (5)$$

2. The diffusion process can be considered to be a conversion of velocity head into pressure head, and the exit velocity, V_x , may be calculated from the Bernoulli expression

$$\frac{V_t^2}{2g} + P_c = \frac{V_x^2}{2g} + P_d \quad (6)$$

Thus

$$V_x = \sqrt{V_t^2 + 2g(P_c - P_d)} \quad (7)$$

To facilitate performance calculations, all losses in the mixing chamber and diffuser have been incorporated in an overall thrust efficiency coefficient, N_t , the value of which must be determined experimentally. Applying this efficiency to the momentum in the fluid stream, the total jet thrust can be evaluated as follows:

$$T_j = \frac{(M_s + M_w)}{g} N_t V_x \quad (8)$$

3. By introducing the momentum drag of the water which is inducted by the missile for both conversion to steam and condensation, the net thrust produced by the system can be computed. It is assumed for simplicity that full free-stream velocity is recovered but in actual missiles only a portion can be recovered because of losses in the boundary layer, thereby reducing the momentum drag.

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III Theoretical Analysis, C (cont.)

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$$T_{md} = \frac{(M_s + M_w) V_m}{g} \quad (9)$$

$$T_n = T_j - T_{md}$$

$$T_n = \frac{(M_s + M_w)}{g} (N_t V_x - V_m) \quad (10)$$

D. LIMITING DISCHARGE PRESSURE

1. It is believed that the limiting discharge pressure of the system is reached when the exit velocity is reduced to a value such that the required exit area exceeds the available exit area. At this point a pressure shock occurs, which travels back into the condensing chamber and destroys the vacuum, thereby making operation unstable. Since the algebraic summation of pressure forces in the axial direction equals the momentum change, an analytical description of the process can be made as follows:

$$\begin{aligned} \Sigma F_x &= \Sigma M \Delta V \\ (P_d - P_c) W A_t &= \frac{(M_s + M_w)}{g} (V_t - V_x) \end{aligned} \quad (11)$$

Inasmuch as the condensing-chamber pressure is extremely small compared to the discharge pressure, the expression can be simplified by assuming P_c to be negligible:

$$P_d A_t W = \frac{(M_s + M_w)}{g} (V_t - V_x) \quad (12)$$

2. The exit velocity, V_x , can be expressed in terms of the mass rate of flow, $(M_s + M_w)$; the exit area, A_t ; and the specific weight, W , of the final mixture. Normally it would be expected that the specific weight of the condensate is that of saturated liquid at the equilibrium temperature. However, because of the high level of turbulence, the nonuniformity of radial mixing, and the degree of condensation, the average specific weight departs from that of an ideal incompressible fluid. This deviation is taken into account by a density coefficient, K , which can be determined experimentally. Evaluating the exit velocity

$$V_x = \frac{(M_s + M_w)}{K A_t W} \quad (13)$$

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III Theoretical Analysis, D (cont.)

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Substituting this expression in Equation (12)

$$P_d A_t W = \frac{(M_s + M_w)}{g} \left[V_t - \frac{(M_s + M_w)}{K A_t W} \right]$$

Since $\beta = \frac{M_w}{M_s}$

$$(M_s + M_w) = M_s (1 + \beta)$$

Resubstituting,

$$P_d A_t = \frac{M_s (1 + \beta)}{W g} \left[V_t - \frac{M_s (1 + \beta)}{K A_t W} \right]$$

From Equation (5), the above expression may be reduced by the following substitution:

$$V_t = \frac{V_s + \beta V_w}{1 + \beta}$$

Thus

$$P_d = \frac{M_s}{g W} \left[\frac{V_s + \beta V_w}{A_t} - \frac{M_s (1 + \beta)^2}{K W A_t^2} \right] \quad (14)$$

3. It can be seen from this expression that as the value of K approaches unity, the limiting discharge pressure is increased. Also evident is the fact that the discharge pressure can be maximized for optimum values of β and A_t . Once the value of K is determined experimentally, the final equation may be utilized to predict the maximum stable discharge pressure for a given set of design conditions. Hence the limiting service depth of the missile can be determined analytically, with a fair degree of reliability. This knowledge is an important consideration in the design of a prototype unit.

IV. TEST PROCEDURE

Detailed descriptions of the test procedure and equipment used were given in Aerojet Reports No. 579, 631, and 675. Since the purpose of this report is a correlation of test results and design parameters, the presentation of descriptive details is not warranted. For general reference, a schematic drawing of the test setup is included as Figure 3 and a photograph of the installation is shown as Figure 4.

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V. RESULTS OF TESTS

A. OPTIMUM DESIGN OF COMPONENTS

1. Water Injector

a. Tests have shown that the water-inlet passages should be designed with a length-to-diameter ratio of at least 5:1 and placed at an angle of inclination to the axis such that their point of convergence lies about one to two chamber-throat diameters upstream from the throat of the condensing chamber. This configuration provides excellent mixing and gives the system very desirable starting characteristics.

b. A study has revealed that, for operation near the surface or for shallow depths, the water passages should be of constant cross-sectional area, to prevent separation of flow at the scoop entrance. This point cannot be overemphasized since drag tests of scoop models have shown that improperly designed scoops result in external diffusion, causing prohibitively high values of missile drag.

2. Steam Nozzle

The steam nozzle can possess a 15° to 20° half-angle divergence and be underexpanded an appreciable amount without adversely affecting the condensing-chamber pressure. To derive the maximum benefit from the low pressure in the condensing chamber, the allowable space within the missile form should be completely utilized to obtain the largest exit area of steam nozzle that is possible. Separation past the throat of the steam nozzle can be delayed by giving the profile a smooth, well-rounded transition.

3. Condensing Chamber

a. To accommodate the condensing chamber within the missile profile, the length must be kept as short as possible. In accordance with this objective, successful operation has been achieved using a chamber with a 5:1 ratio of length to throat diameter. This value is remarkably low, inasmuch as commercial injectors require ratios of 8:1 or more to perform satisfactorily. A limit exists on the reduction in chamber length which may be accomplished, before performance is adversely affected. This limit is governed by the finite distance required for condensation. Also important is the fact that, as the chamber length is reduced, the angle of inclination of the water jet increases until the departure from axial flow is excessive and a large portion of the useful water momentum is never recovered.

b. Test results have also indicated that the length-to-diameter ratio of the exit section should be kept within 1:1 to 2:1 for best results. Significantly, investigation has shown the superiority of straight exit sections over diverging sections having various divergence angles, from

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V Results of Tests, A (cont.)

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the standpoint of diffusion efficiency. A complete explanation for this phenomenon is not offered. However, it should be noted that the condensed mixture is a fluid moving at an abnormally high velocity, 300 to 400 ft/sec, and is in a metastable condition, being composed of highly turbulent particles of steam and water droplets. Furthermore, it is generally believed that at high discharge pressures, the diffusion process is not a conventional pressure conversion but takes place through a hydraulic "jump" or shock. Since the mixture is not an incompressible fluid, there is no reason to expect it to possess the normal diffusion properties of an incompressible fluid such as water.

c. As mentioned previously, the ratio of water-inlet area to condenser-throat area is a significant parameter. For the most favorable starting properties that it is possible to achieve, ratios of about 0.7 or less are required, while for efficient operation at appreciable depths, where the back pressure is high, the ratio should be as large as is compatible with stability limits. It can be seen immediately that the two requirements are incompatible from the standpoint of obtaining the maximum performance over the entire range of operating conditions. Various attempts to develop a satisfactory variable-exit-area device have been made without much success. However, results show that a compromise in design can be made which enables the system to operate with satisfactory performance under a wide range of conditions. Experience indicates that an area ratio of about 0.7 to 0.8 is a reasonable value on which to base the design of an exit section for a free-running missile.

B. ANALYSIS OF TEST DATA

1. Design Curves*

An investigation was conducted to determine the performance characteristics of a steam-jet condenser utilizing saturated steam at 150 psig and mass flow rates slightly less than 1.0 lb/sec. In the determination of the overall thrust efficiency coefficient, η_t , the measured thrust was compared with the theoretically calculated thrust for the points of operation. The velocity of the steam jet was computed on the basis of isentropic expansion from the initial steam pressure down to the condensing-chamber pressure. By combining the effects of friction, divergence, and losses due to under-expansion, a nozzle velocity coefficient of .90 was decided upon for use throughout the calculations.

* The curves shown in Figures 5 through 15 were plotted from the data obtained during the test program conducted on the small-scale steam-jet condenser. Unless otherwise noted, the tests were performed using nearly saturated steam at an inlet pressure of 150 psig and a flow rate of 0.92 lb/sec. To establish the initial ram pressure for surface conditions, in tests where depth simulation was required, a missile velocity of 170 ft/sec was assumed and used throughout.

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V Results of Tests, B (cont.)

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a. The curves in Figures 5 to 9 indicate the effect on performance of the mixture ratio of water to steam, β , and the area ratio, R , for depths of operation from the surface down to 800 ft. It has been found that the losses in the momentum exchange and mixing process between water and steam are relatively small. On the other hand, results indicate that the majority of the losses occur in the diffusion process. Directly connected with this phenomenon is the effect of the area ratio and the mixture ratio on the efficiency of diffusion. The higher the area ratio, within limits, the more closely the diffuser wall conforms to the fluid jet surface, thereby reducing turbulence and separation losses. Similarly, higher mixture ratios provide more complete condensation of the steam and result in a fluid stream approaching a uniform, incompressible jet which can be diffused with fewer losses. Examination of the curves plotted from the experimental data indicate that high values of R result in appreciable increases in thrust efficiency. Also evident is the fact that the efficiency is increased by using higher mixture ratios, especially at the greater depths. The results indicate that at the higher area ratios, .90 and .80, the mixture ratio at the surface should be chosen from 25 to 30 to ensure the maximum performance with depth. However, at the lower area ratios, .50 to .70, the optimum mixture ratio lies between 20 and 25 at the surface. A mixture ratio of 10 is indicated as the limit below which starting of the system becomes unreliable. An upper limit for β of 30 would be reasonable since no benefit is derived from ratios in excess of this. The results presented in these curves may be used directly in the selection of design points.

b. Although not as useful from a design standpoint, the curves in Figures 10 to 13 present the results in a more obvious form. The absolute quantity, net thrust, is used as an index of performance. It can be seen that when R is .90 and β is 25 at the surface, the net thrust is relatively constant down to a depth of 800 ft.

c. The experimental results for the determination of the average density coefficient K are given in Figure 14. As was expected from the previous discussion of the density coefficient, its value is increased with increasing mixture ratios. The effect of higher area ratios similarly increases the value of K . It should be pointed out that these are average values taken from a large number of experimental points and may have a variation of $\pm 5\%$. However, the values of K may be used with reasonable accuracy to predict the limiting stable discharge pressure of a design point.

d. The final curves, presented in Figure 15, illustrate the effect of motive steam pressure on the maximum stable discharge pressure. The particular data are for a unit having an area ratio, R , of .50. A series of stability curves are shown for progressively increasing steam pressures, P_s , from 65 to 180 psia. It is evident that a significant increase in the maximum stable discharge pressure is achieved. From the data an extrapolation was made for a steam pressure, P_s , of 300 psia, shown as a dotted line. This curve indicates a system which is stable for all depths to 1000 ft and slightly greater.

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V Results of Tests, B (cont.)

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e. The photographs shown in Figures 16, 17, and 18 illustrate the effect of depth on the shape of the exit jet. Taken through the window of the high-pressure tank, they show the jet configuration at surface conditions, 500-ft depth, and 1000-ft depth, respectively. The manner in which the high pressures progressively confine the condensing envelope is evident from the photographs.

2. Starting Conditions

a. Tests have shown that with the proper selection of water-inlet to condenser-throat area ratio and the various other design parameters, the system may be started under any sequence of fluid flows. The response of the system has been excellent, stable operation being instantly established with the rapid entry of either fluid. Although tests have been performed with area ratios, R , as high as 1.20, it has been found that a value for R of .90 is the practical limit above which starting becomes unreliable. The surface mixture ratio, β , is 25 under these test conditions. As the value of β is decreased, the limiting value of R for reliable starting properties is also decreased. For values of β from 10 to 15 an area ratio of .70 or less is recommended.

b. The starting phenomenon has been investigated for back pressures greater than atmospheric pressure. For designs in which R is .70 and β is 20, excellent starting characteristics have been obtained for back pressures corresponding to depths of 50 ft. Under conditions of a pre-evacuated condensing chamber, starting of the system has been accomplished at back pressures corresponding to depths of almost 300 ft. However, regardless of these efforts, the starting problem must be completely investigated through the medium of free-running missile tests since actual conditions cannot be duplicated in a static test. Such an investigation might result in the development of special closures for the condensing chamber.

3. Performance at Various Depths

a. From the test data compiled, the efficiency of thrust recovery (actual thrust/theoretical thrust) for surface operation has been established at about 95% for optimum design conditions. At greater depths this efficiency decreases to about 80% for the same design conditions.

b. Experience indicates that a design which performs satisfactorily over the entire range of operating conditions should have an area ratio, R , of .70 to .80 and a mixture ratio, β , of 20 to 25. Under these design conditions and at a depth of 800 ft, the system would produce about 65% of the net thrust available at the surface. This results in approximately a 25% reduction in velocity at 800 ft depth as compared to surface operation. If operation at an area ratio of .90 proves feasible for a free-running missile, then the system would produce approximately constant net thrust in going from the surface down to a depth of 800 ft.

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V Results of Tests, B (cont.)

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4. Stability Characteristics

It has been determined that stability, as measured by the limiting discharge pressure, is dependent on the thrust of the fluid jet, the nature of the fluid, and the throat area of the condensing chamber. The stability of the system is increased with increased motive steam pressures. Rapid variations or fluctuations in the steam conditions do not have any effect on the stability of the system if it is properly designed. All the test results indicate that the full-size hydroductor will perform with satisfactory stability at high back pressures which exist at great depths.

C. TESTS ON THE FULL-SCALE STATIC HYDRODUCTOR

Recent test-firings have been performed on a full-scale steam-jet condenser utilizing a 4.5-in.-dia Alclo motor. The unit was designed from the small-scale test data presented herein. The tests conducted to date have been entirely successful and the results obtained from this program have, in general, fulfilled all expectations. The recording instrumentation in the condensing chamber has registered considerable vacuum, definitely proving that condensation is being accomplished and operation of the system is taking place as intended. Thrust measurements have shown that the performance of the system is equal to or slightly better than that of the hydroduct motor alone, operating at surface conditions. This unit was designed for an area ratio, R , of .70 and a mixture ratio, β , of 25 at surface conditions. Thus, the feasibility of the system has been proved conclusively; and free-running missile test-firings will be required to establish the capabilities of the system under Service conditions. Figure 19 is a photograph of a hydroductor drag missile, which is very similar in proportions to the prototype hydroductor missile to be used in the free-running test-firings.

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SYMBOLS

V_m	=	Free-stream velocity, ft/sec
V_s	=	Velocity of steam jet, ft/sec
V_w	=	Spouting velocity of sea water into chamber, ft/sec
V_t	=	Final mixture velocity of condensate, ft/sec
V_x	=	Exit velocity after diffusion, ft/sec
P_c	=	Condensing-chamber pressure, feet of water
P_d	=	Ambient water pressure, feet of water
P_s	=	Steam pressure before entering nozzle, psia
M_s	=	Steam mass rate of flow, lb/sec
M_w	=	Water mass rate of flow, lb/sec
β	=	Water-to-steam mass ratio, M_w/M_s
N_t	=	Overall thrust efficiency coefficient
A_w	=	Water inlet area, ft ²
A_t	=	Area of condensing-chamber throat, ft ²
R	=	Ratio, A_w/A_t
K	=	Density coefficient of condensed mixture
θ	=	Angle between water stream and longitudinal axis, degrees
H_s	=	Enthalpy of steam at P_s and before expansion, Btu/lb
H_c	=	Enthalpy of steam at P_c after expansion, Btu/lb
C_s	=	Steam-nozzle velocity coefficient
C_w	=	Water-nozzle velocity coefficient
W	=	Specific weight of water, lb/ft ³
T_j	=	Total jet thrust, lb
T_{md}	=	Momentum drag of inducted water, lb
T_n	=	Net thrust, lb

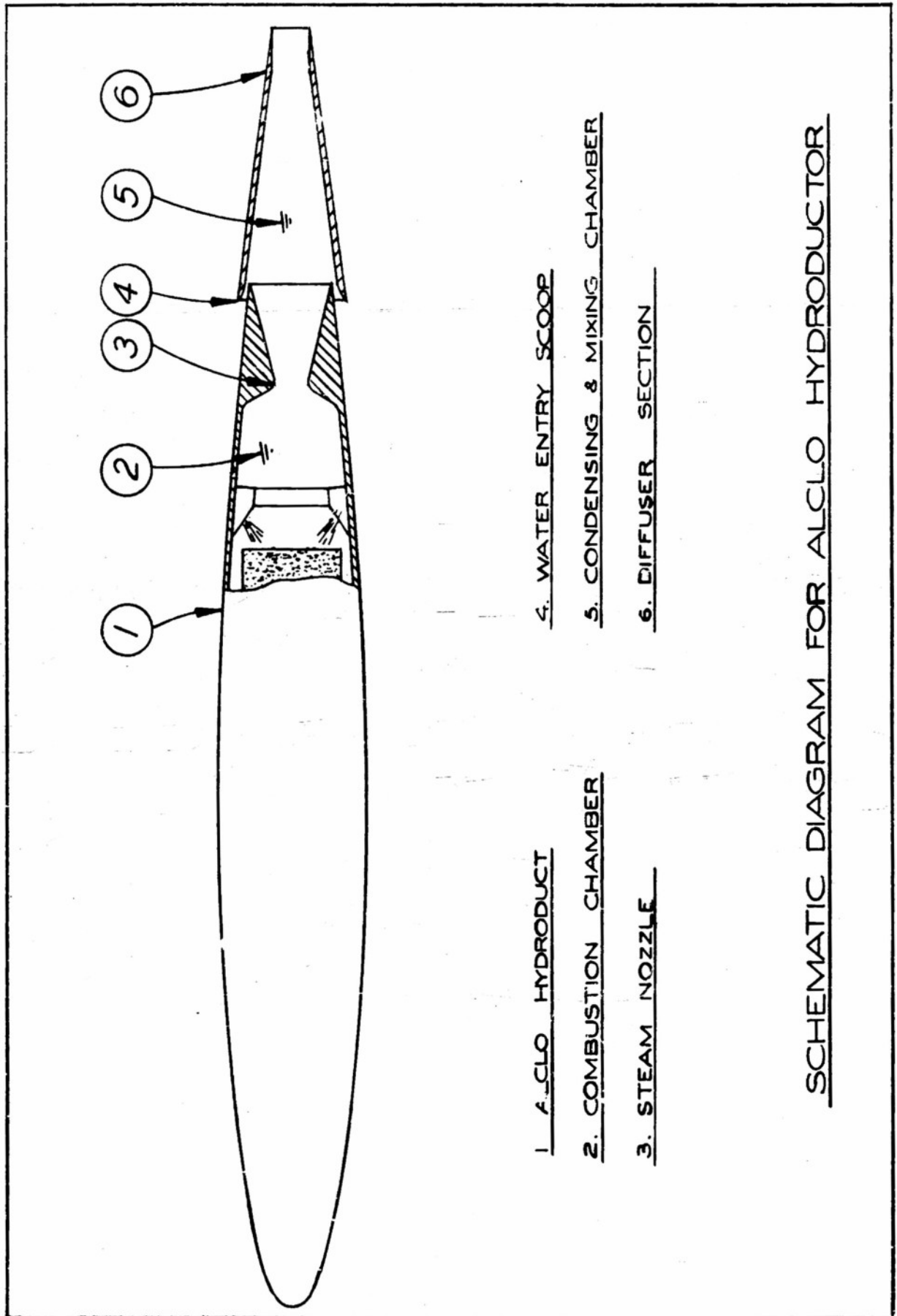
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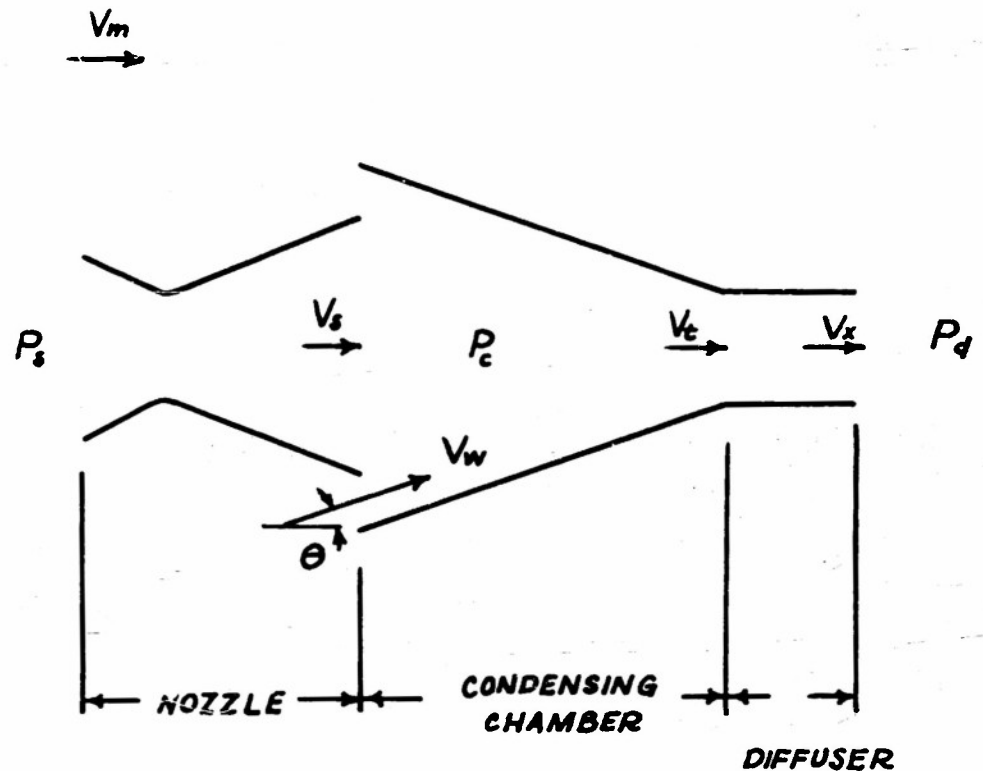
SCHEMATIC DIAGRAM FOR ALCLO HYDRODUCTOR

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THEORETICAL ANALYSIS

C-4172

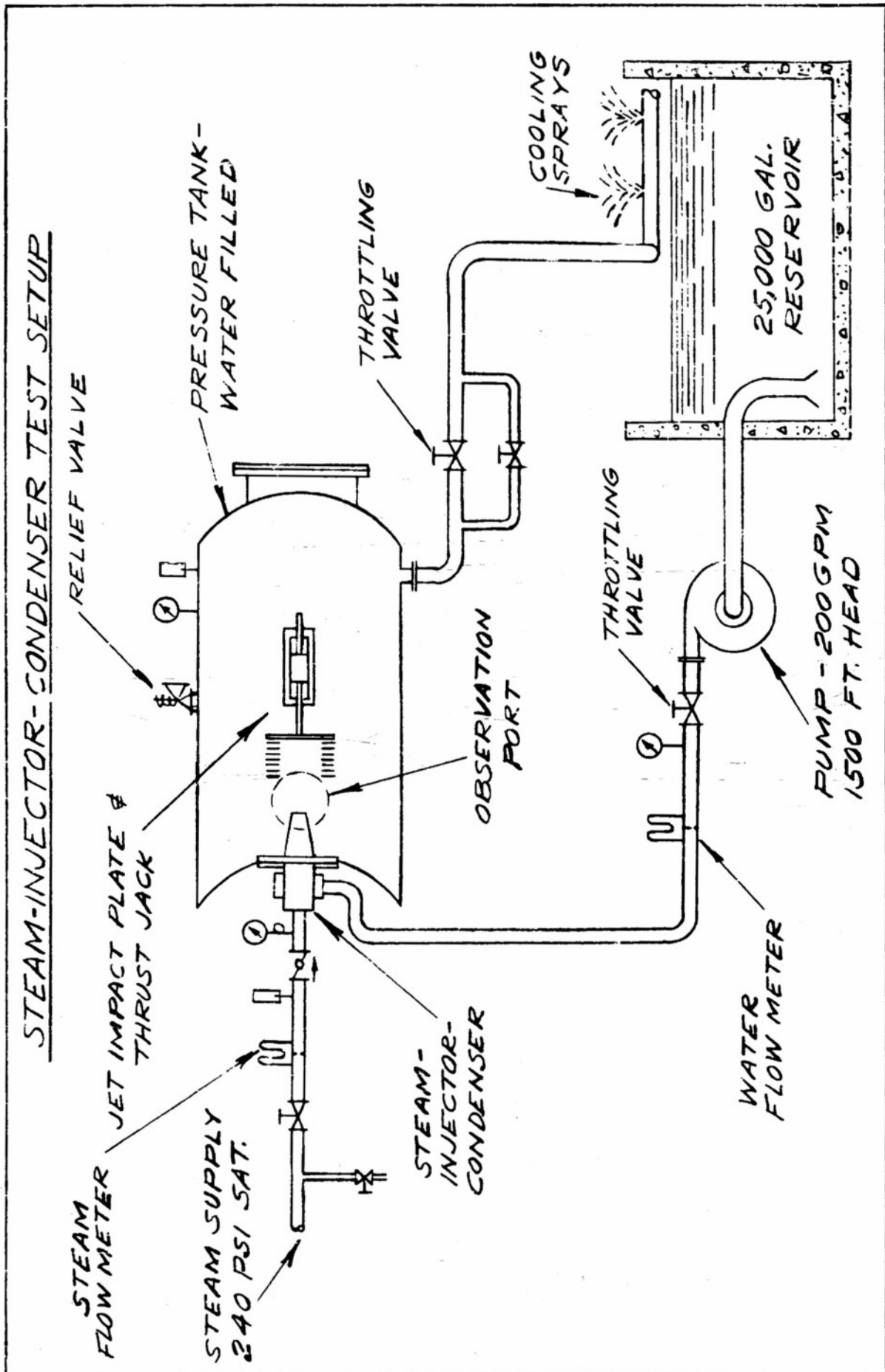


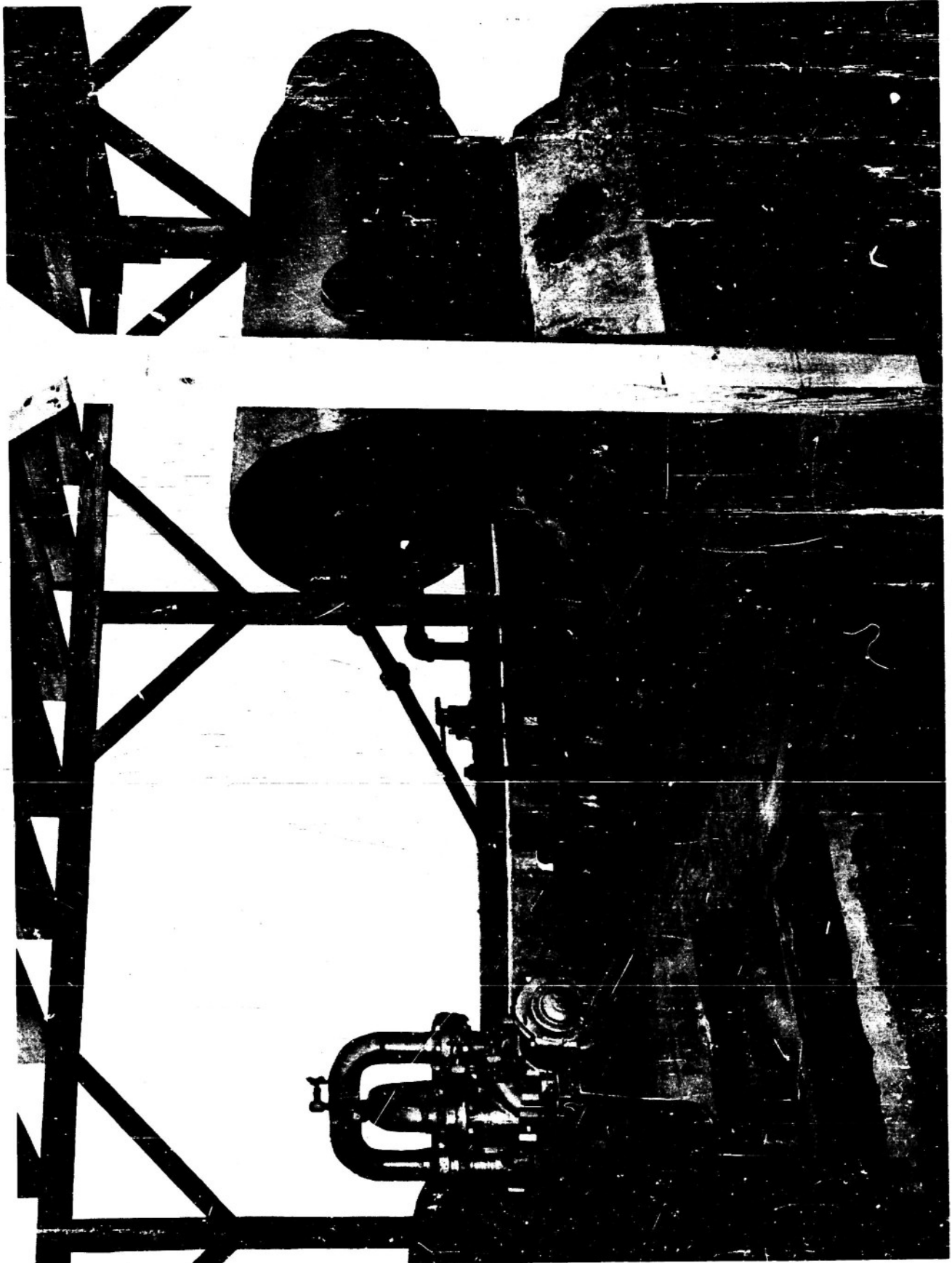
SCHEMATIC DIAGRAM OF STEAM-JET CONDENSER

Figure 2

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CURVE NO. 4100 7-22-51 EGL





General View of Steam-Injector-Condenser Test Setup

1251-573

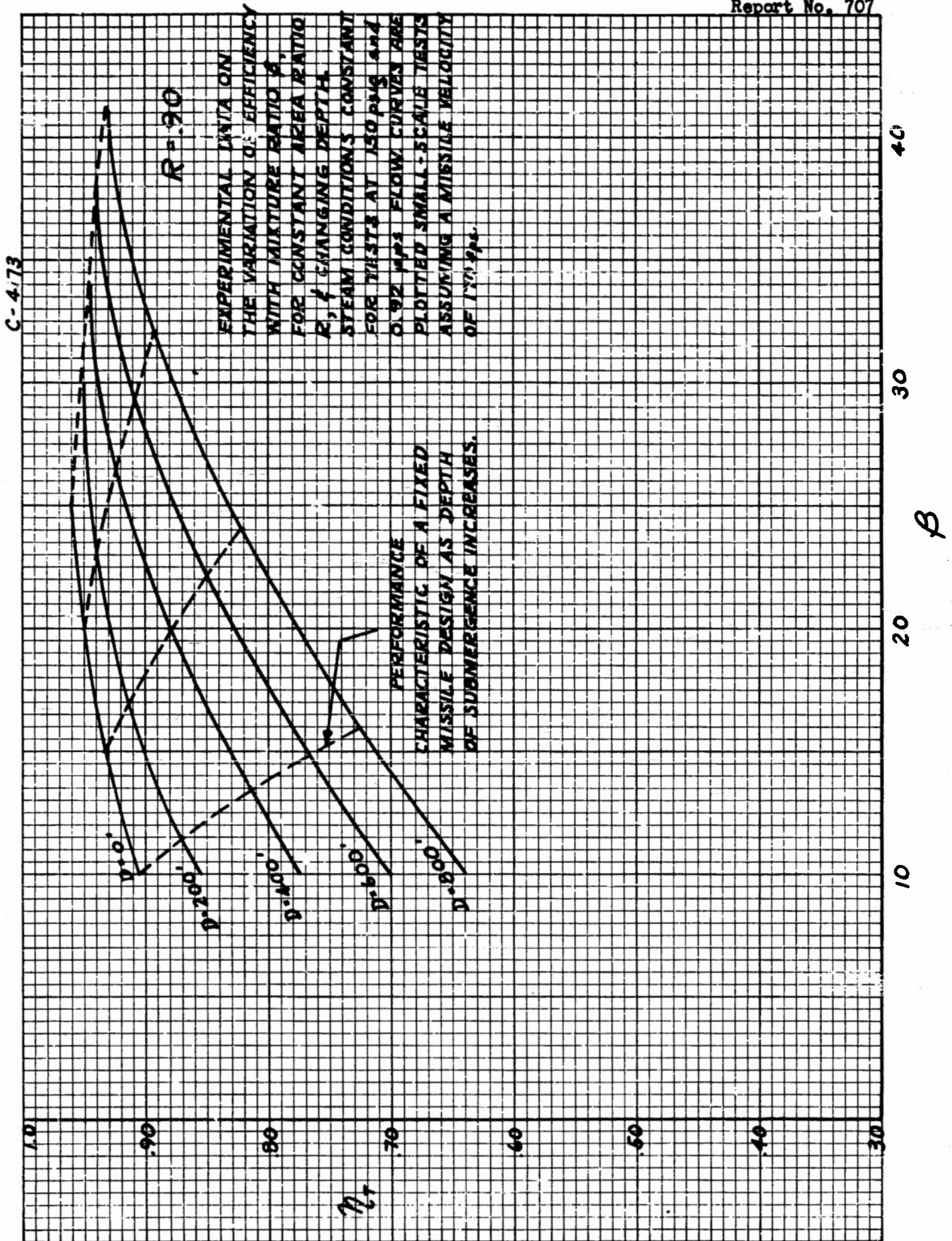


Figure 5

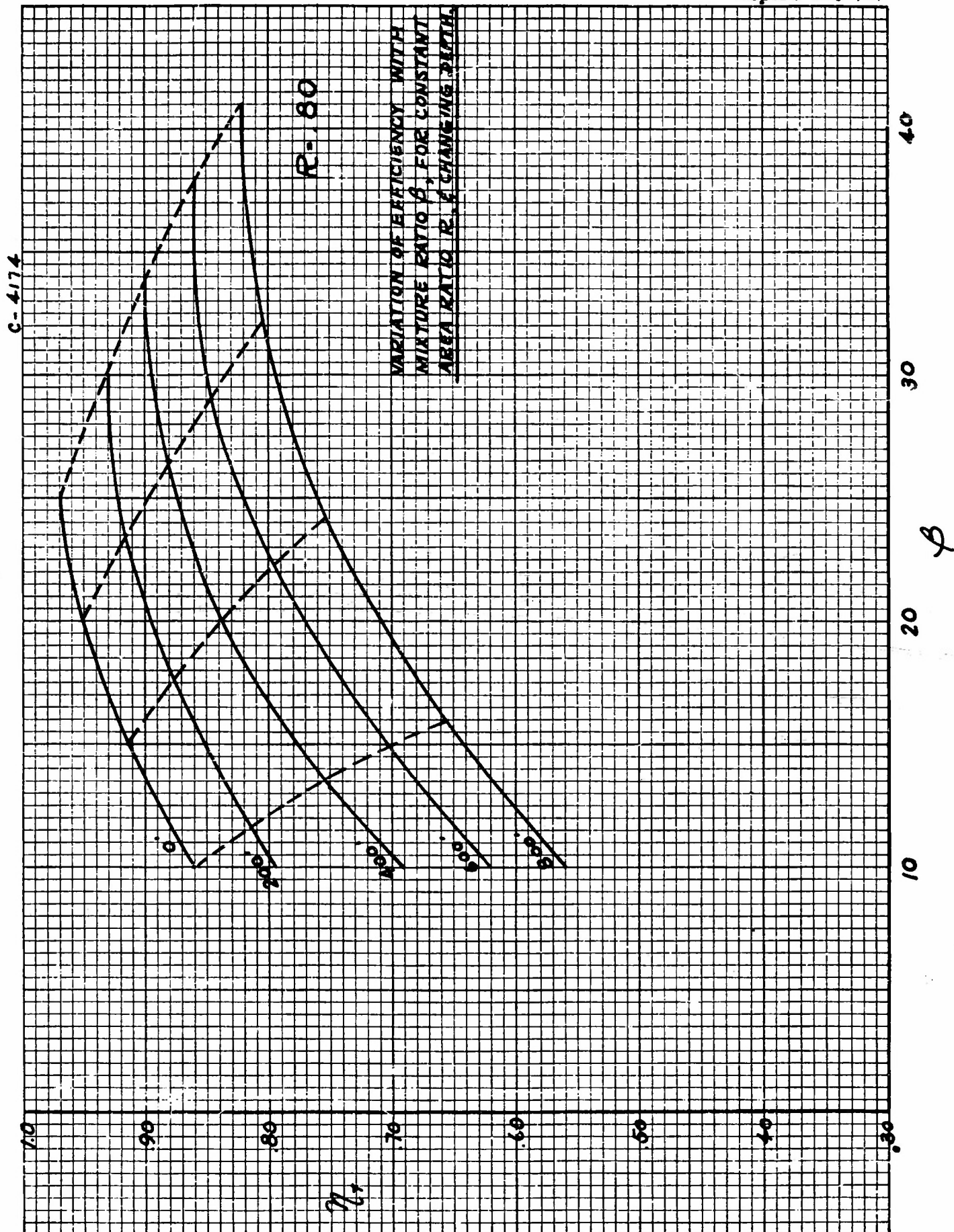


Figure 6

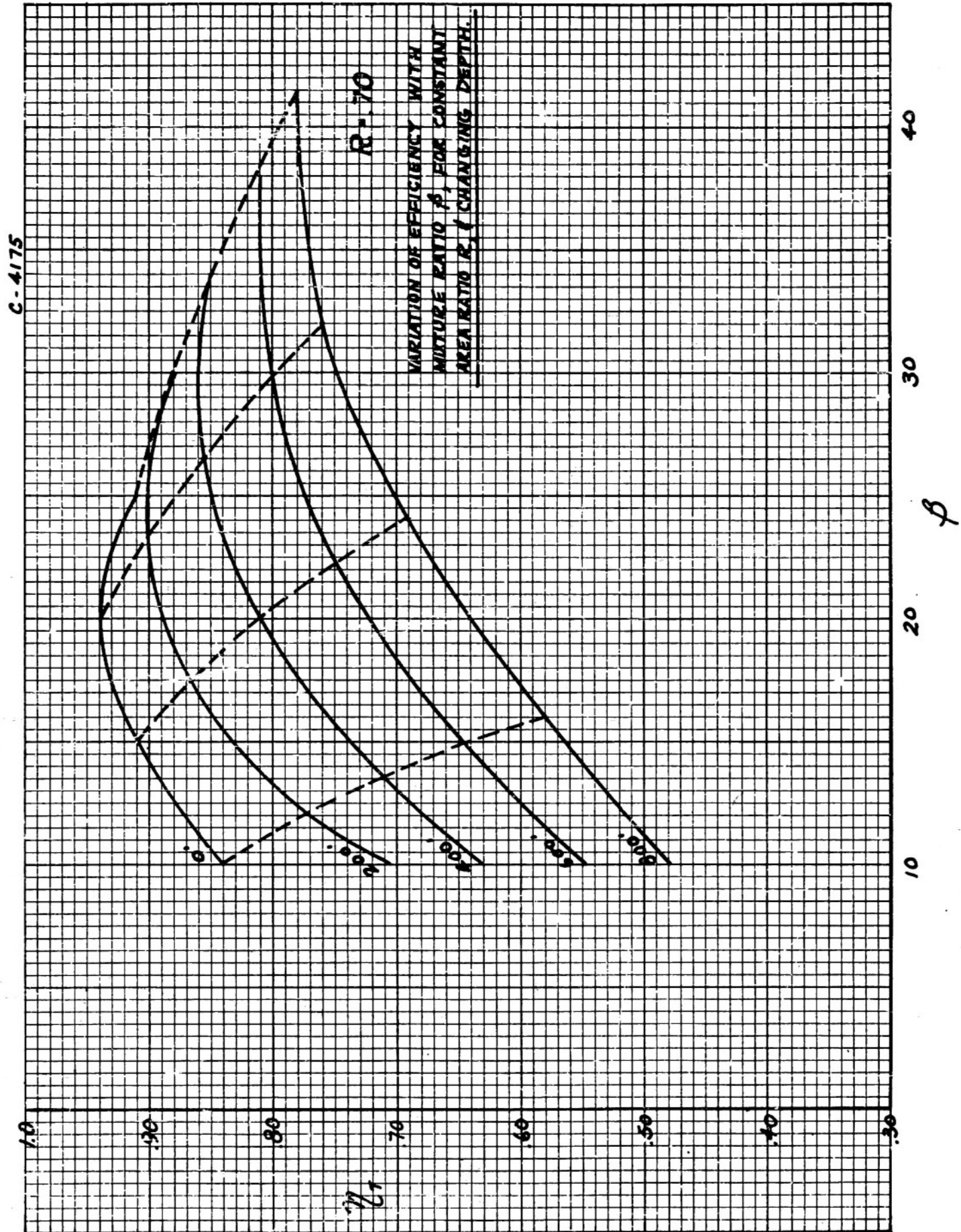


Figure 7

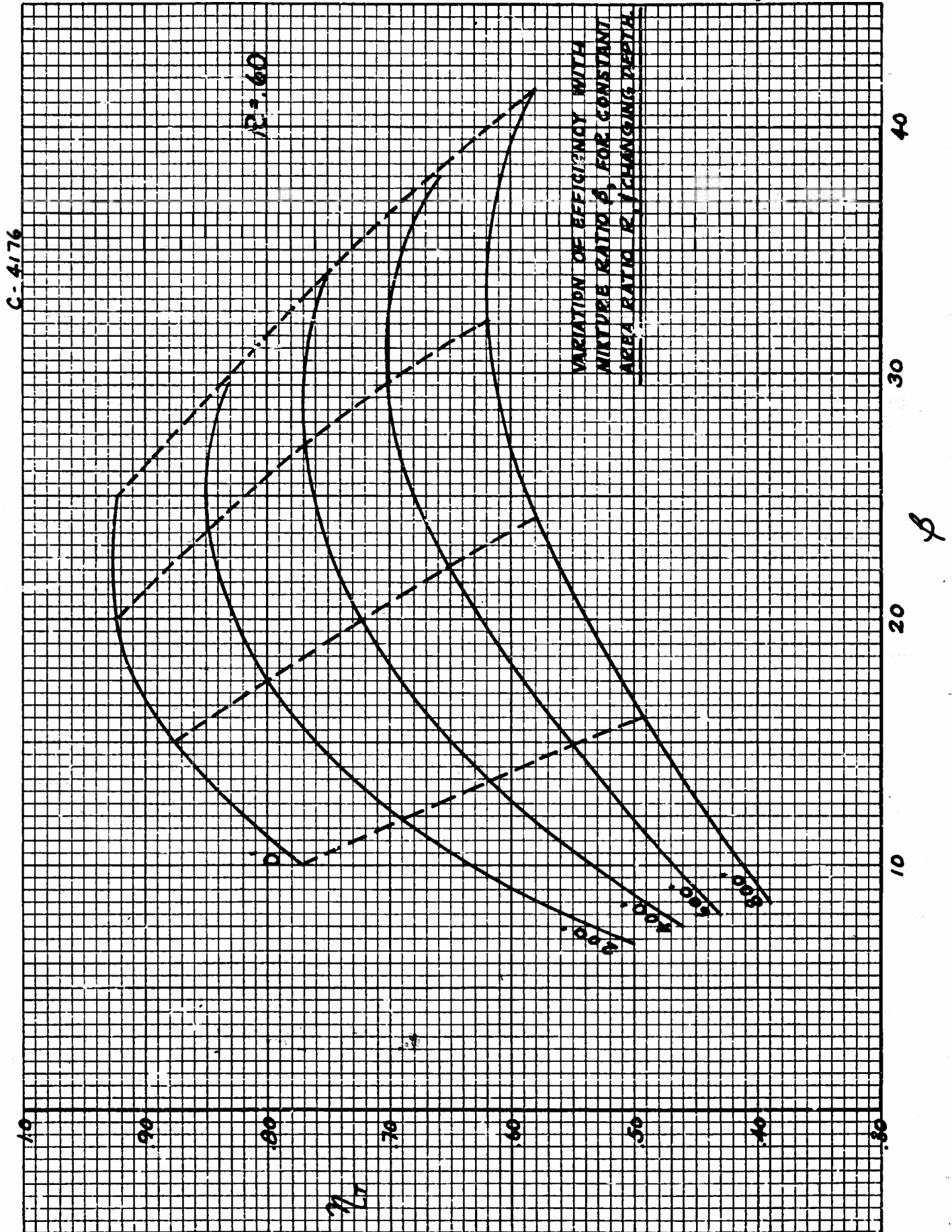


Figure 8

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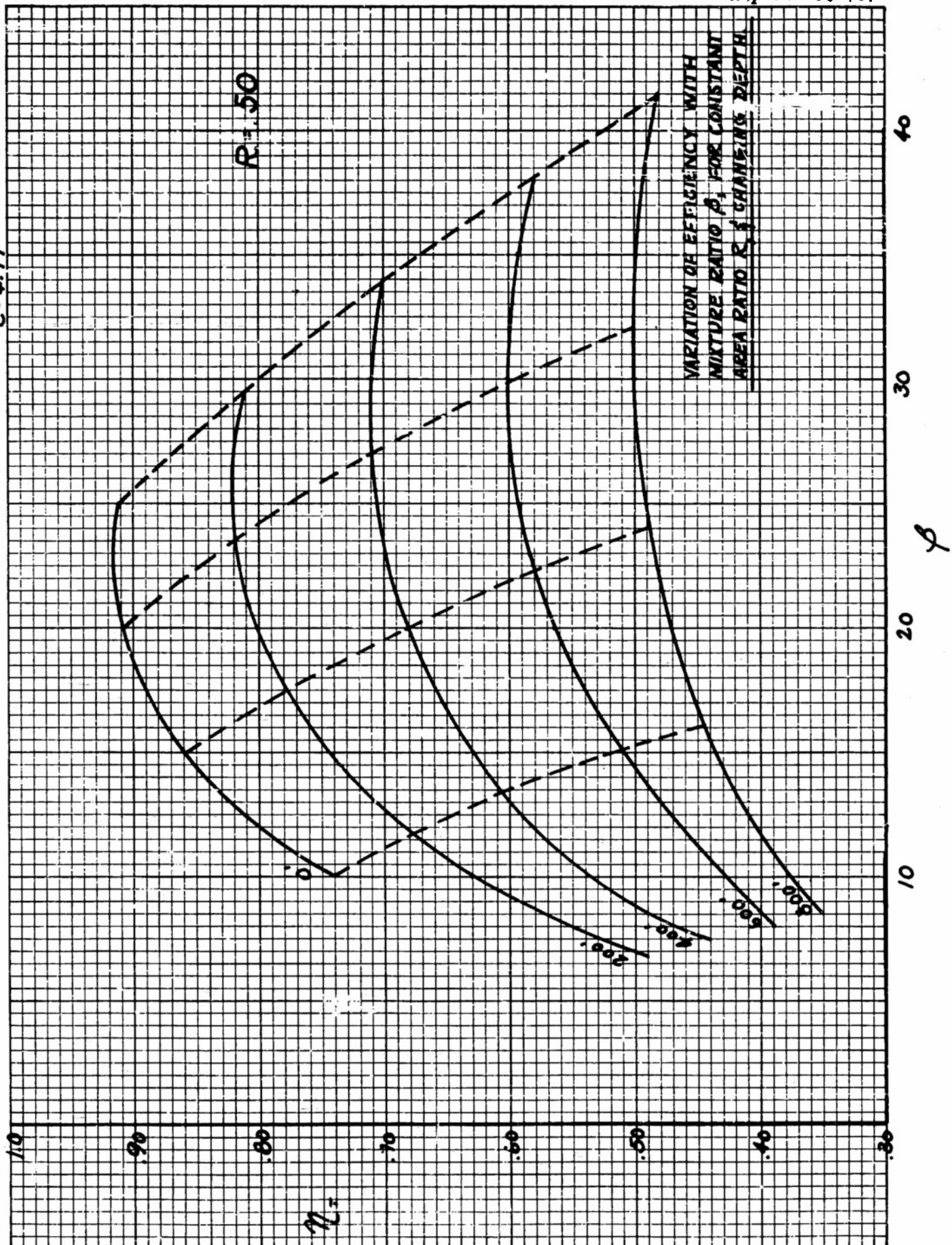
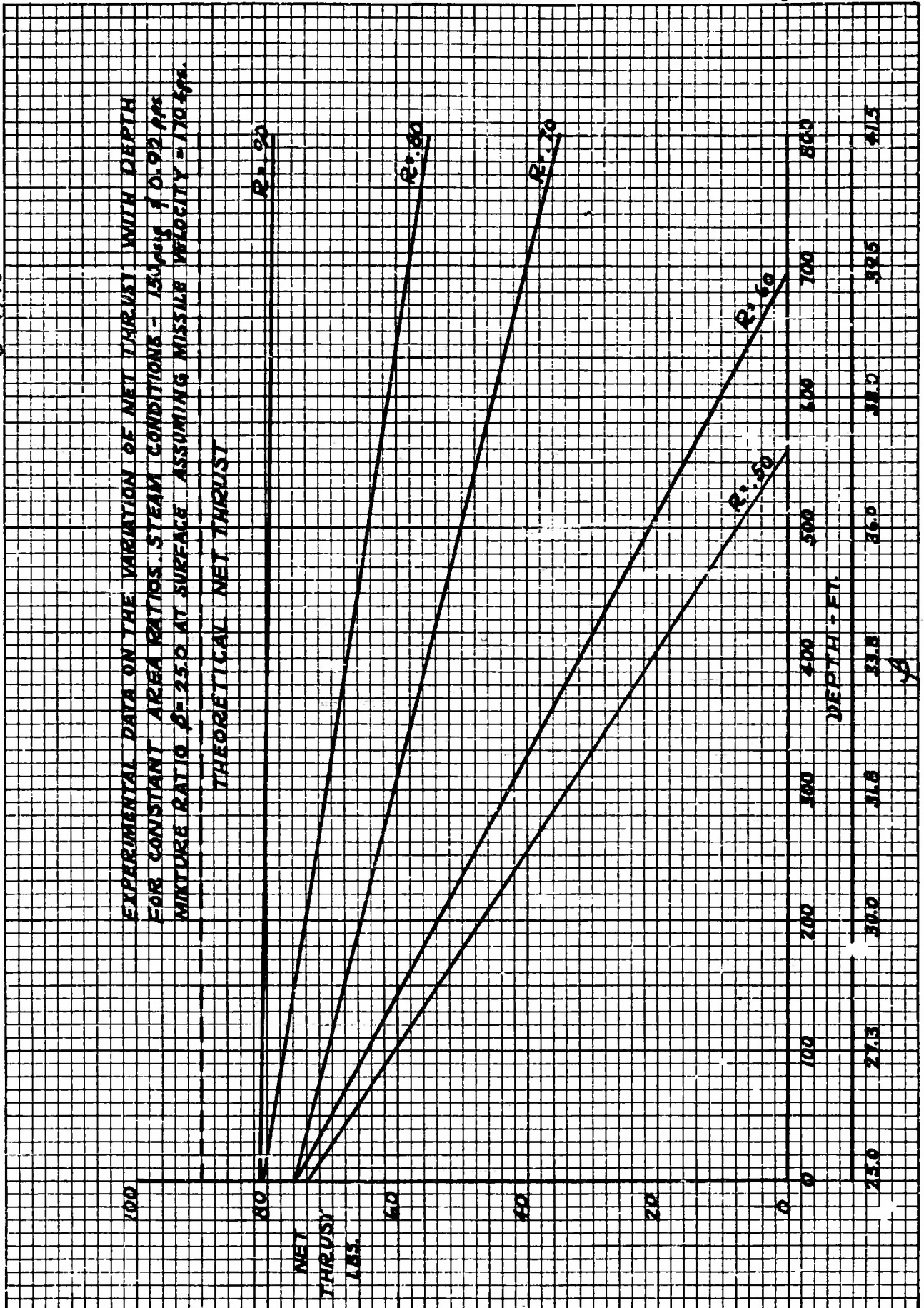


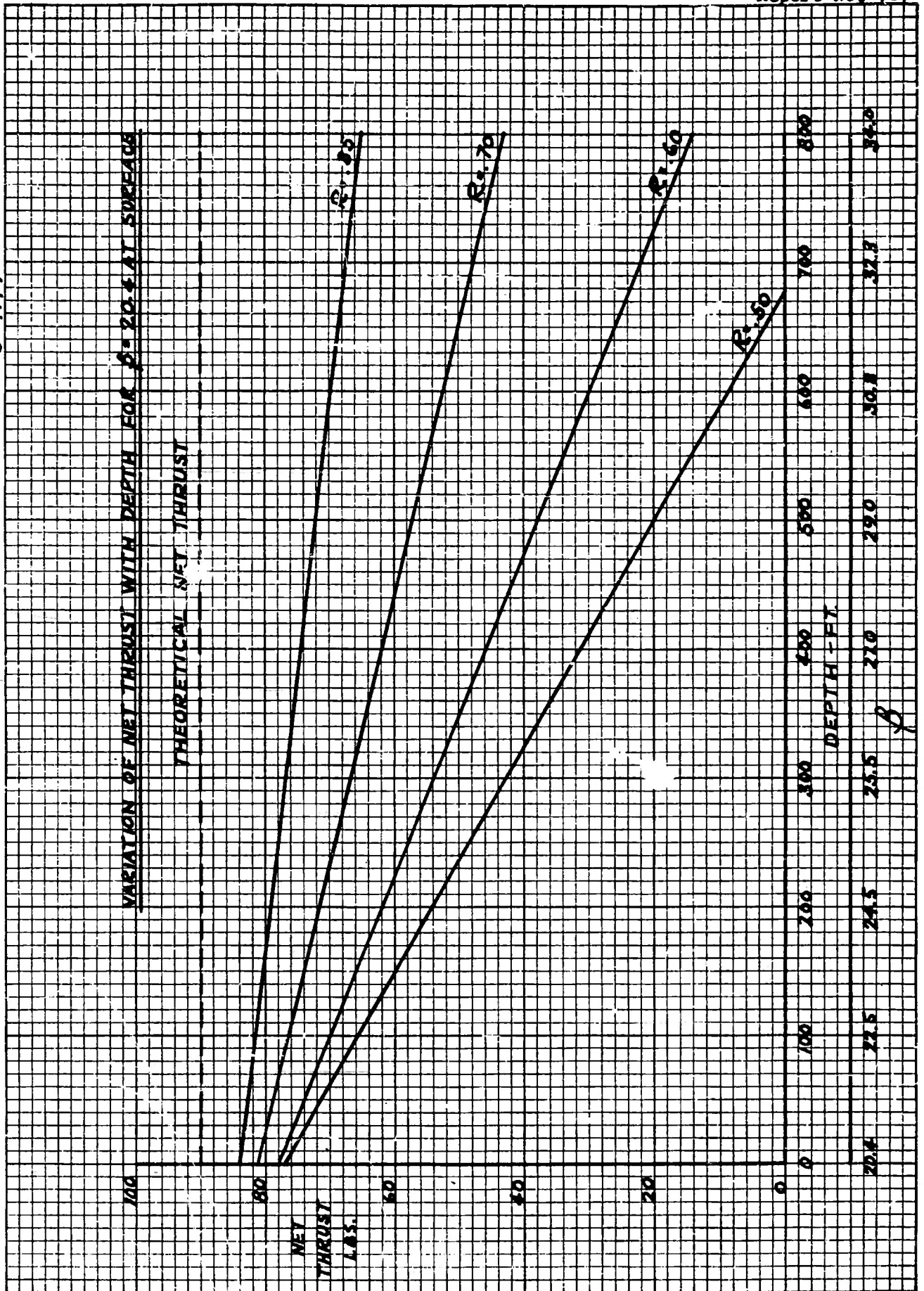
Figure 9

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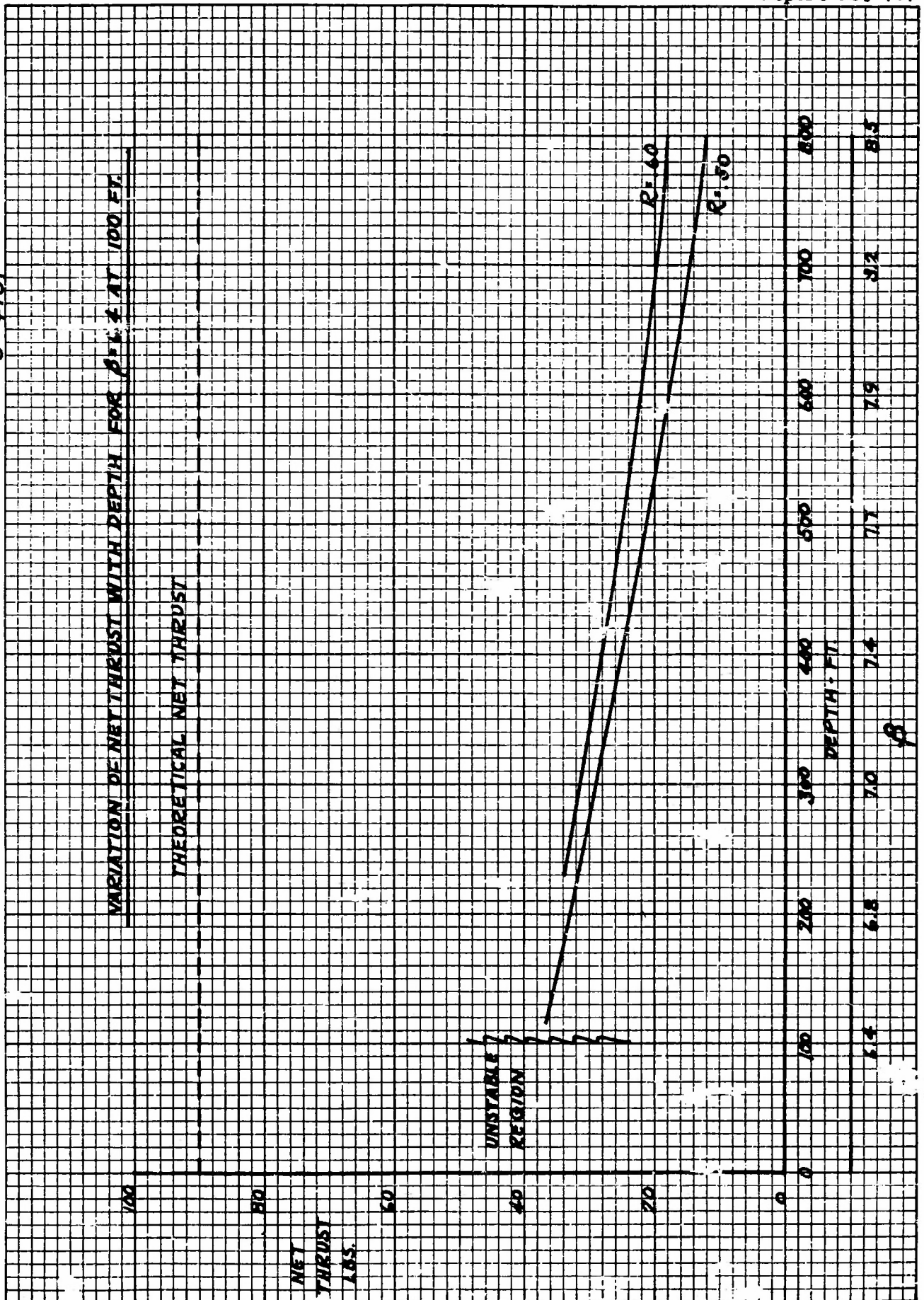


C-4180

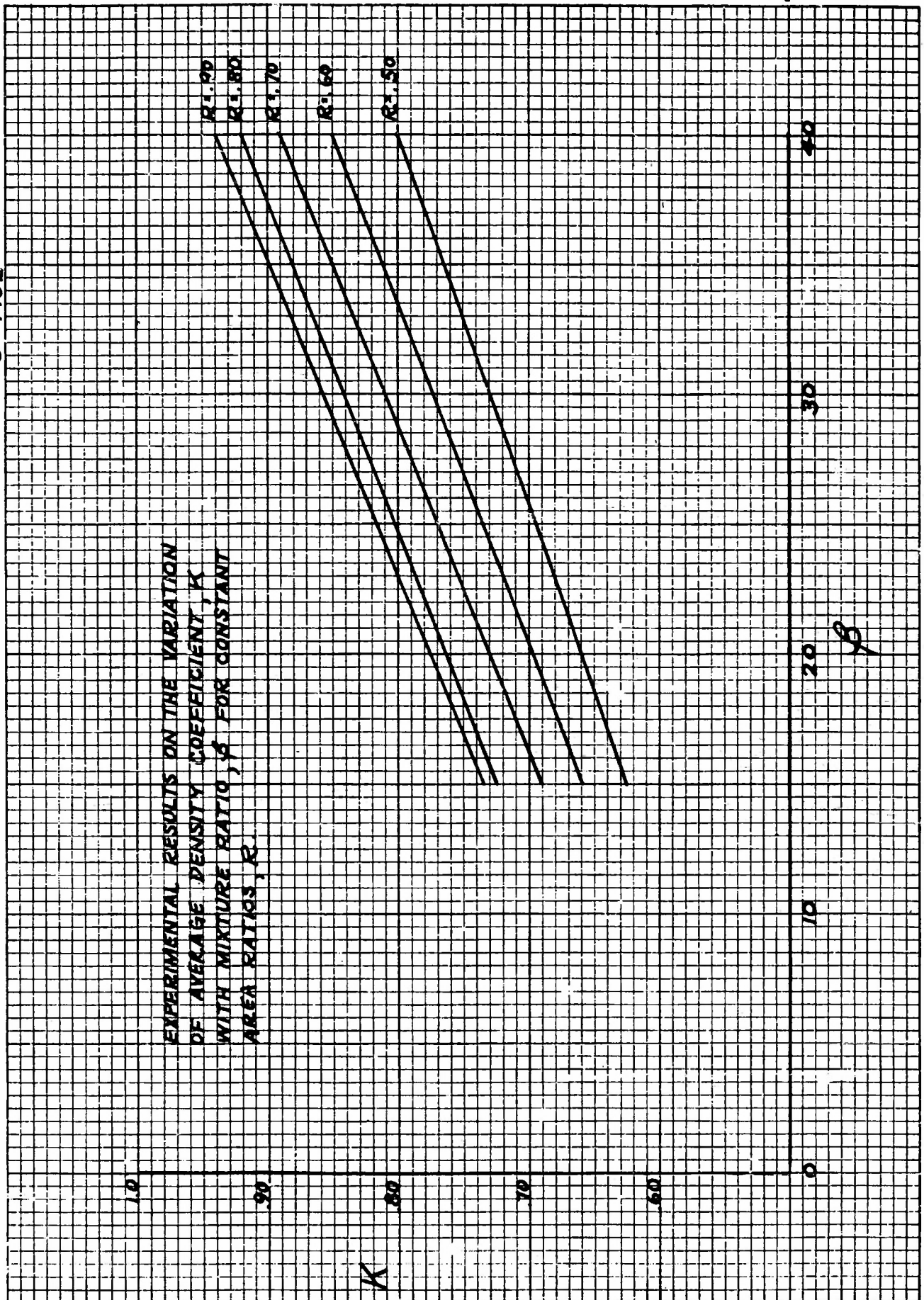


Figure 12

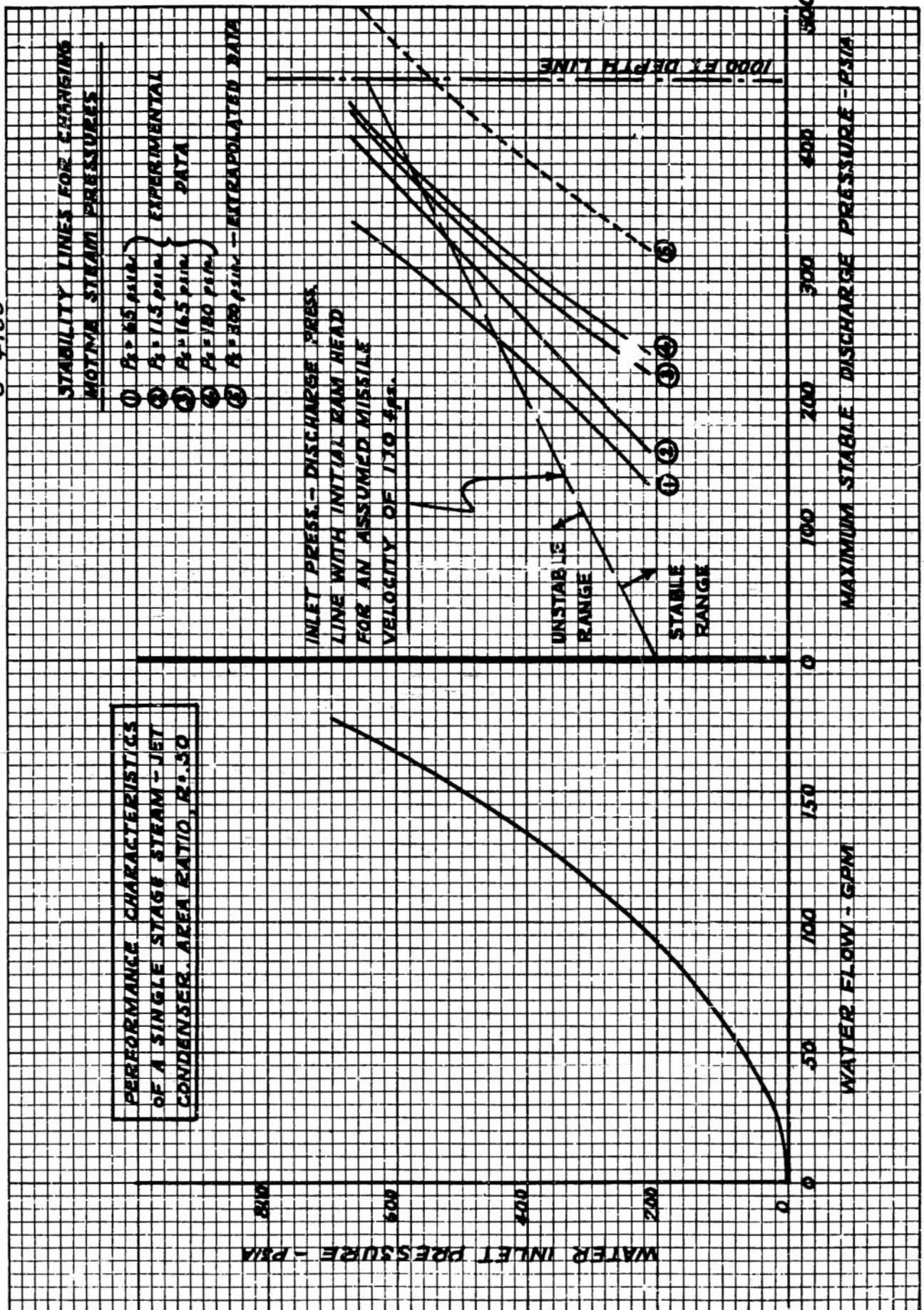
C-4181



C-4182



C-4183



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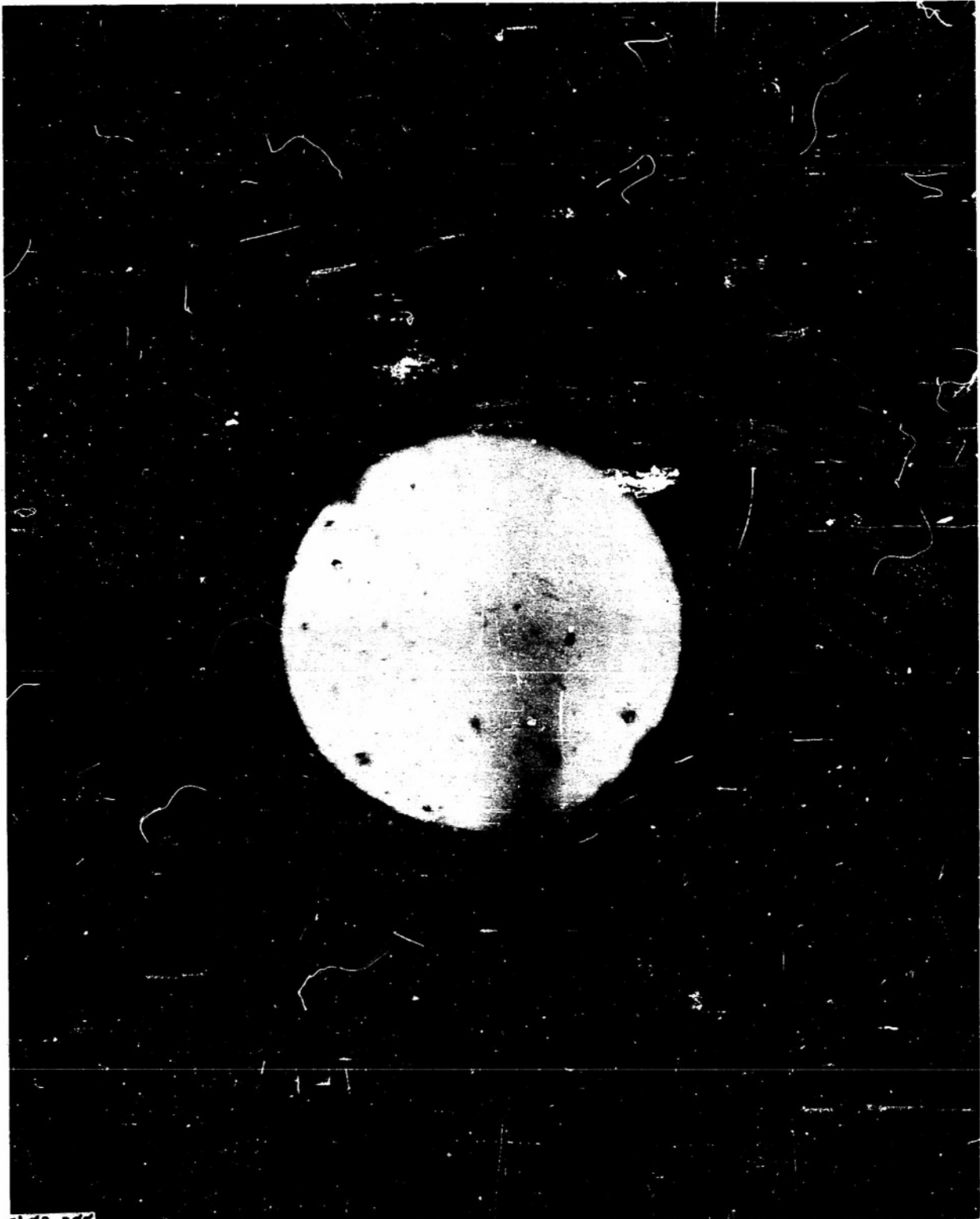
Report No. 707



Condensed Jet at Surface

Figure 16

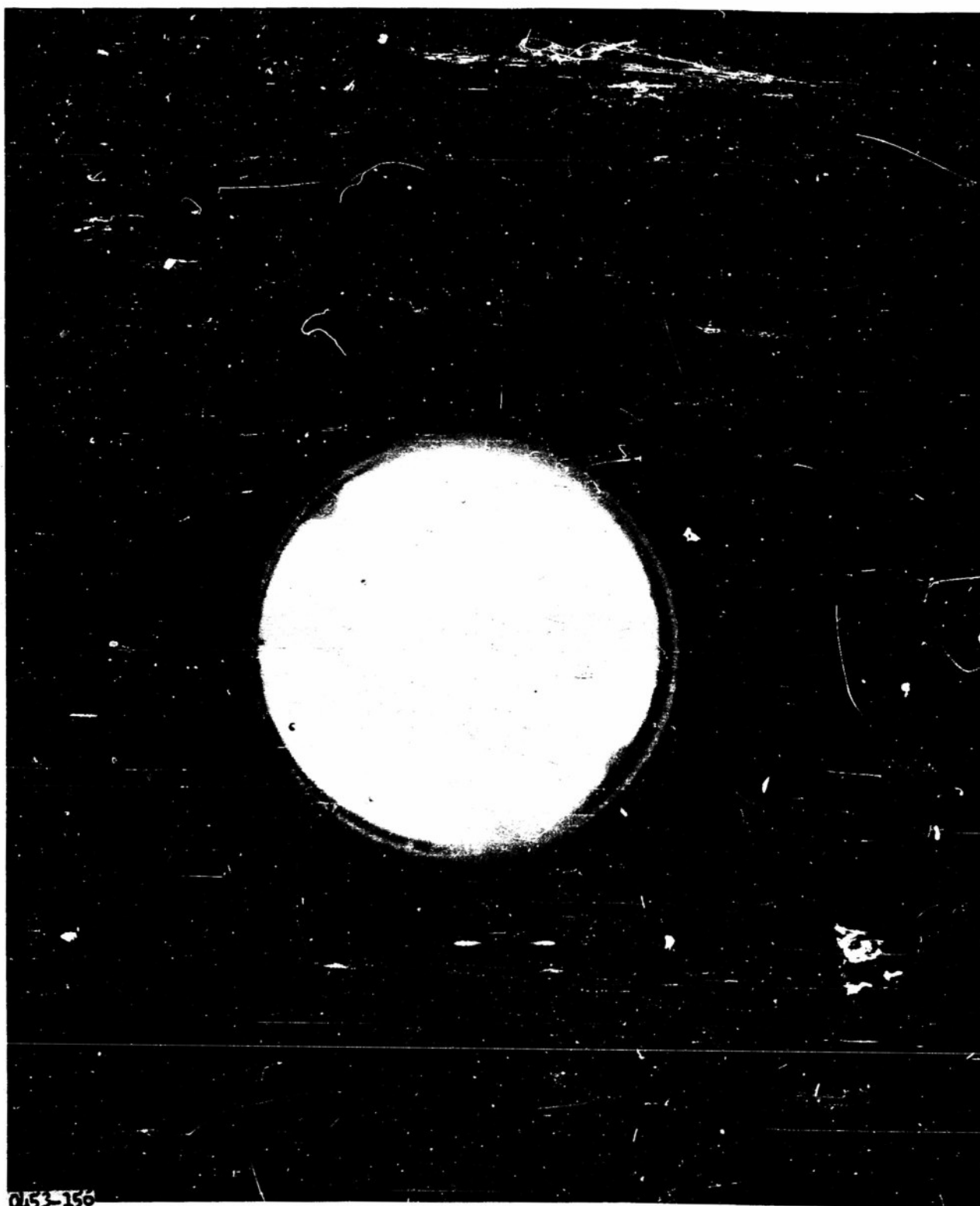
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Condensed Jet at 500 ft Depth

Figure 17



Condensed Jet at 1000 ft Depth

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